Bio-drainage for Management of Waterlogging and Soil Salinity

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Abstract

Biodrainage is defined as the process of removing the excess soil water through transpiration using bio-energy of the plant and radiation energy of the sun. It is an option to prevent the development of water logging in canal command areas. It has specific role in checking advancement of seepage from water courses and a viable option for safe disposal of large volume of saline water available in saline areas underlain with surface and sub surface drainage systems. In the absence of provision of adequate drainage, waterlogging and associated soil salinity is the major impediment to sustainability of irrigated agriculture. Though, conventional engineering drainage technologies such as subsurface or vertical drainage are able to combat the problem but are costly and generate huge quantities of drainage effluent which is difficult to dispose. Further, these options are quite successful where large tracts affected by waterlogging and salinity exist in continuity. Biodrainage, which removes the excess soil water by deep rooted fast-growing trees through evapotranspiration using bio-energy is proposed as an alternate to above engineering approaches. In rainfed areas, it can be used for interception of ground water flow and recharge control whereas in irrigated areas it is useful for controlling rise in water table, intercepting seepage water from canals and channels. Irrigation of high transpiring forest species has also been put forward for reuse of wastewater and conservation of nutrient energy into biomass and thereby bringing multiple benefits such as fuel wood production, carbon sequestration, environmental sanitation and eco-restoration. For finding an appropriate biodrainage solution, water balance between precipitation, irrigation input of water vis-à-vis water requirement of the agro-ecosystem and groundwater hydrology need understanding. Biodrainage potential of tree flora is a cardinal component for designing and implementing biodrainage projects. Consumptive water use of plants varies with the age, geometry, soil properties, water table, salinity and climatic conditions. This varies between 6500 to 28000 m^3 ha^{-1} $year^{-1}$ and under ideal conditions, a tree canopy may lower water tables by 1–2 m over a time period of 3–5 years. Trees of the genes such as *Eucalyptus, Populus, Casuarina, Dalbergia, Syzigium, Acacia, Prosopis, Leucaena* etc. are reported effective to lowering a shallow water table and reverse salinity trends. Amongst different trees studied at different places, Eucalyptus was preferred because it grows fast in wide range of conditions, goes straight thus low shading effect on associated crops, and has luxurious water consumption in excess soil moisture conditions. Trees bio-harvest meagre amount of the salts and do not remove the salts from the soil thus may not be a good alternative when irrigation water is too saline. In cases where biodrainage results in salt accumulation, it needs to be integrated with conventional drainage technologies to make the system sustainable. Small and marginal farmers may not be able to set part of their farm aside for bio drainage activities therefore biodrainage technology may be more suitable on large farms or public lands. However, integration of trees such as *Eucalyptus* and *Populus* along with crops in a uniified agroforestry system or on approach roads or field bunds or on dykes of pond in an integrated farming system will be a viable preposition. For effective understanding and implementation, several case studies on the role of biodrainage for

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managing waterlogging and salinity are also cited. The information in this document is discussed under the following sub-heads: (1) Introduction, (2) Extent of waterlogging and soil salinity, (3) Mechanism of biodrainage, (4) Situations suitable for biodrainage application, (5) Planning and design for biodrainage plantations, (6) Suitable plant species, (7) Case studies, (8) Advantages, (9) Constraints, (10) Future research and policy issues, (11) Conclusion.

1. Introduction

Introduction of canal irrigation without adequate provision for drainage in arid and semi-arid regions results in water table rise leading to waterlogging and secondary salinization in large areas in irrigation commands. These problems are the result of a multitude of factors, including seepage from unlined canals, inadequate provision of surface and subsurface drainage, over irrigation and use of poor quality groundwater for irrigation. Globally about 10% of the land area is affected by waterlogging (Setter and Waters, 2003) and over 6% by salinity (FAO, 2008). In India, about 6.7 million ha of land is affected by different levels and types of salinity, out of which nearly half are under irrigated agriculture (ICAR, 2010). Severely waterlogged saline soils occur in about two million ha area in arid/ semi- arid north western states of Punjab, Haryana, Rajasthan and Gujarat and one million ha each in the coastal and black cotton Vertisol regions of India. It is projected that about 13 million ha area in irrigation commands of India will be affected by waterlogging and soil salinity by 2025. Use of saline/ alkali groundwater and climate change will further accentuate the threats (CBIP, 2015). Waterlogged saline soils apart from environmental degradation result in poor crop yields by reducing crop yields by as much as 80% (Shabala, 2011) and finally in abandoning the land from cultivation. In India, yearly crop loss due to waterlogging has been estimated to be more than 2 m tons (ICRISAT, 2009). The economic loss was estimated to be about Rs. 23,900/ha with a total annual loss of Rs. 1669 million (about US$ 37 million) from the waterlogged saline area of Haryana, India (Datta and Jong, 2002). The crop yields and relative yield loss caused due to waterlogging and soil salinity of major crops are presented in Table 1 (Joshi, 1994). Thus, twin menaces of waterlogging and salinization represent serious threats to the sustainability of irrigated agriculture and calls for appropriate reclamation measures.

For favourable plant growth, optimum balance of water, air and salt in the root zone is a primary requirement which can be achieved by providing adequate drainage. No doubt, the conventional technologies such as surface, subsurface or vertical drainage overcome the problem of waterlogging and salinity, but they have limitations like high cost of construction and subsequent maintenance cost and safe disposal of drainage effluent during reclamation and afterwards. Disposal of drainage effluent which contains nutrients, salts, agro-chemicals and other pollutants in water bodies had resulted in pollution of many river basins like the Indus basin in Pakistan, the Murray-Darling Basin Catchment in Australia, San Joaquin Valley in USA and various river systems in India. To combat drainage problem of such an extent, the technology needed to be less expensive, location specific, sustainable and environment friendly for its large-scale adoption by the farmers.

Biodrainage could be a viable option. It is a combined drainage-cum-disposal system. Biodrainage can be defined as “pumping of excess soil water by deep-rooted vegetations through evapotranspiration using their bio-energy”. Reliance on capability of vegetation to reduce water table has been reported promising both in India as well as in other countries. The main physiological feature of such vegetation is profuse transpiration whenever the root system comes in contact with groundwater. The biodrainage technique is eco-friendly as the biodrainage plantations purify the environment by absorbing greenhouse gases and releasing oxygen into the environment, environmentally safe as it does not generate any drainage effluent to dispose, economically attractive because it requires only an initial investment for planting the vegetation, and when established, the system could produce economic returns by means of fodder, wood or fiber harvested and has an additional advantage in term of carbon locked in the timber. The first documented use of the term biodrainage can be attributed to Gafni (1994). Prior to that date Heuperman (1992) used the term bio pumping to describe the use of trees for water table control.

Table 1. Losses due to water logging and soil salinity

Crop	Normal lands	Salt affected lands	Waterlogged lands
Paddy	39.9	21.8 (45)	23.0 (42)
Wheat	26.0	15.8 (40)	18.6 (38)
Cotton	16.3	6.1 (63)	3.7 (77)
Sugarcane	636.8	330.2 (48)	247.5 (61)

2. Waterlogging and Soil Salinity

A soil is said to be water logged when the ground water table gets linked to soil water in the crop root zone and remains like this for the remaining period in a year (Michael and Ojha, 2006). It results restriction of the normal circulation of the air, decline in the level of oxygen and increase in the level of carbon dioxide. The critical depth depends on the kind of crop, but waterlogging is commonly defined as light for a soil profile depth of 3 m for substantial parts of the year, and moderate for less than 1.5 m. The severe degree occurs with a water table at 0-30 cm depth, and also included is ponding, where it rises above the surface (FAO, 1994). As an illustration, rise in water table at different places in Haryana (north India) between 1974 and 2004 is shown in Figure 1.

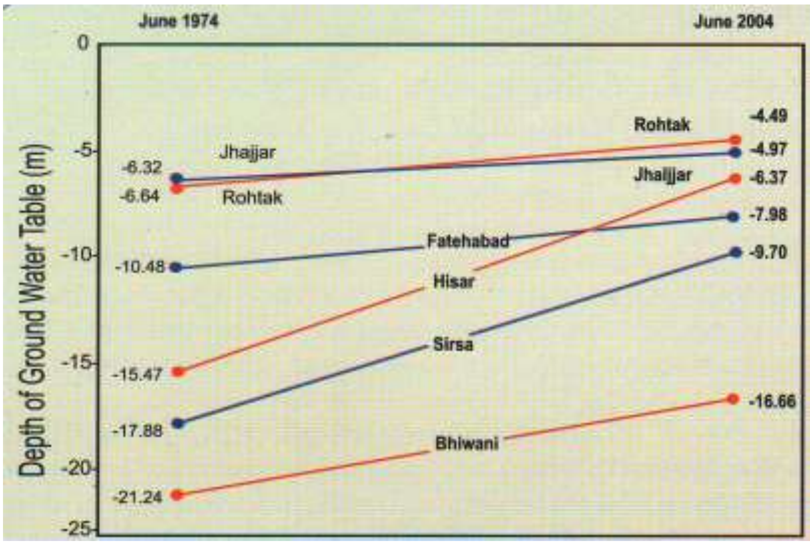

Figure 1, Trend in rise in water table in Haryana (Source: Jeet Ram et al., 2008)

Soil salinity is another problem in arid and semi arid regions. It refers to presence of excess amount of soluble salts in soil water creating its high osmotic pressure which restricts crop water uptake and ultimately resulting in poor plant growth. Salinity occurs when salts are transported to surface by rising water and got concentrated with evaporation. Several species of trees and crops can be grown in alkali, saline and saline water-logged soils. Relative tolerance of crops and trees to salt stress is reported in Tables 2 and 3.

Table 2. Relative Tolerance of Crops and Grasses to Soil ESP

Tolerant **ESP, 35-50**	**Moderately tolerant** **ESP, 15-35**	**Sensitive** **ESP <15**
Karnal grass (*Leptochloa fusca*) Rhodes grass (*Chloris gayana*) Para grass (*Brachiaria mutica*) Bermuda grass (*Cynodon dactylon*) Rice (*Oryza sativa*) Dhaincha (*Seshania aculeate*) Sugarbeet (*Beta vulgaris*) Teosinte (*Euchlaena maxicana*)	Wheat (*Triticum aestivum*) Barley (*Hordeum vulgare*) Oat (*Avena sativa*) Shaftal (*Trifolium resupinatum*) Lucerne (*Medicago sativa*) Turnip (*Brassica rapa*) Sunflower (*Helianthus annus*) Safflower (*Carthamus tinctorius*) Berseem (*Trifolium alexandrinum*) Linseed (*Linum usitatissimum*) Onion (*Allium cepa*) Garlic (*Allium sativum*) Pearl millet (*Pennisetum typhoides*)	Gram (*Cicer arietinum*) Mash (*Phaseolus mungo*) Chickpea (*Cicer arietinum*) Lentil (*Lens esculenta*) Soybean (*Glycine max*) Groundnut (*Arachis hypogea*) Sesamum (*Sesamum oriental*) Mung (*Phaseolus aureus*) Pea (*Pisum sativum*) Cowpea (*Vigna unguiculata*) Maize (*Zea mays*) Cotton (*Gossypium hirsutum*)

Source: CSSRI, Karnal, 2007

Table 3. Relative Tolerance of Tree Species to Soil Alkalinity

Average pH_2 (0-120 cm)	**Fuel-wood/Timber species**	**Fruit trees**
More than 10.0	*Prosopis juliflora* (Pahari kiker) *Acacia nilotica* (Kikar) *Casuarina equisetifolia* (Australian pine)	*Achras Japota* (Chikoo)
9.0 to 10.0	*Tamarix articulata* (Frans) *Terminalia arjuna* (Arjun) *Eucalyptus tereticornis* (Safeda) *Albizzia lebbek* (Papri) *Pongamia pinnata* (Siris Karanj) *Sesbania sesban* (Dhaincha) *Emblica officinalis* (Amla)	*Zizyphus maurtiana* (Ber) *Carissa carandus* (Karaunda) *Psidium guajava* (Amrood) *Syzygium cumini* (Jamun) *Phoenix dectylifera* (Khajoor) *Aegle marmelos* (Bael)
8.2 to 9.0	*Dalbergia sisoo* (Shisham) *Morus alba* (Sehtoot) *Grevilla robusta* (Silver Oak) *Azadirachta indica* (Neem) *Tectona grandis* (Teak) *Populus deltoids* (Poplar)	*Punica granatum* (Anar) *Prunus persica* (Aru) *Pyrus communis* (Nashpati) *Vitis vinifera* (Angoor) *Mangifera Indica* (Aam)

Source: Singh et al., 1993

3. Mechanism of Biodrainage

The root systems of trees intercept saturated zone or unsaturated capillary fringe above water table and control shallow water table. The primary objective of a bio-drainage system is to lower a shallow groundwater table to below the "critical depth" (2 m below ground surface is generally accepted as a safe depth) of the capillarity-induced evaporative processes that cause salinization (Heuperman et al. 2002; Kapoor 2001). For efficient biodrainage system, trees should be fast growing having high rate transpiration system so that they absorb sufficient quantity of water from the capillary fringe located above the ground water table. The roots of herbaceous annuals have little or no contact with water table. The absorbed water is translocated to different parts of plants and finally more than 98% of the absorbed water is transpired into the atmosphere mainly through the stomata. Under ideal conditions, a tree canopy may lower water tables by 1–2 m over a time period of 3–5 years (Gafni and Zohar, 2001; Heuperman et al., 2002; Kapoor, 2001). This combined process of absorption, translocation and transpiration of excess ground water into the atmosphere by the deep-rooted vegetation conceptualizes biodrainage.

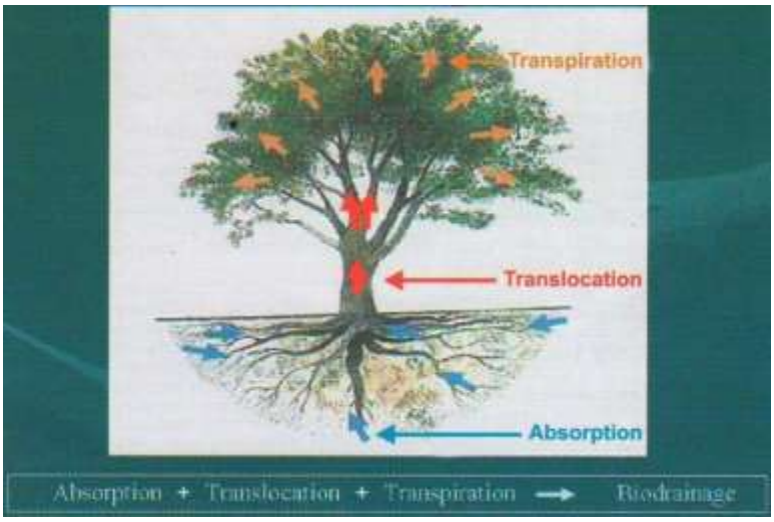

Figure 2. Concept of Biodrainage

4. Situations Suitable for Biodrainage Application

Depending upon land use, biodrainage mechanism can be applied both in dry land/rainfed and irrigated agriculture. In rainfed systems, bio-draining ability of vegetation can be utilized mainly for recharge control, interception of ground water flow and discharge enhancement.

Extensive clearing of area for agricultural development and cultivation of annual crops with shallow rooting crops may result in higher recharge and ultimately rise in water table and causing waterlogging and salinity as was observed in Kyabram, Australia. Re-vegetation of recharge areas by deep rooted tree plantation minimizes deep seepage losses in the higher parts of the landscape to minimize discharge problems referring recharge control and reduction of localized salinity and discharge problems in lower part of the landscape. Excessive evaporative demand of newly planted vegetation may lead to dry landscape causing reduced river flow, drying of well and increase in groundwater salinity. The interception of groundwater flowing through permeable layers overlying low permeability strata reduce discharge problems further down the slope. In dry land areas, extensive clearing upsets the hydrological balance, resulting in saline discharge in low lying land areas, which affects agricultural productivity and water quality in stream systems. Reclamation techniques for dry land salinity in waterlogged discharge areas focus on the restoration of the hydrological balance by planting biodrainage vegetation using the concept enhanced evapotranspiration (Heuperman, 2000).

In irrigated areas biodrainage can be useful for control of rise in water table, intercepting seepage water from channels and management of salinity as in convention drainage system as discussed below.

a. ***Water table control***: Shallow water table causes root zone soil salinization which adversely affects crop growth. Biodrainage in irrigation areas lowers water tables below the critical depth, which is defined as the depth at which capillary salinization is negligible.

b. ***Channel seepage interception*****:** Channel seepage can be a major contributor to water table rise and consequently can cause water logging and salinity problems in the adjoining land. Water quality of seepage water is normally good which if intercepted can be productively used by crops. In cases if seepage water is not intercepted and left to evaporate it will increase salinity.

c. ***Biodrainage cum conventional drainage systems*****:** For the optimum growth of biodrainage crops also, salt accumulation in the root zone should not exceed the threshold level. Where biodrainage results in salt accumulation, engineering assistance is needed to make the system sustainable.

5. Planning & Design for Biodrainage Plantation

The primary requirement for planning and deciding the location for putting drainage plantings is the catchment water balance and precise identification of recharge and discharge areas in the landscape. The following issues should be considered in the development of biodrainage systems:

- Water balance: In irrigated areas due to net incremental recharge ground water table starts rising causing water logging. To overcome the above problem, the objective of any drainage scheme, is to achieve water balance before the ground water table rises up to the critical depth, which in general may be taken as 2.0 m below ground level. Plantations of deep rooted trees with high rates of transpiration should extract ground water equal or more than the net recharge so that water table is kept below the critical depth root zone. Tree plantations often use water at higher rates because of the high aerodynamic roughness which may be even more pronounced because of the so-called clothesline effect prevailing in rows of trees, substituting for a conventional drain pipe.
- Area under plantation for water balance: For sustainable water balance, the area to be covered under biodrainage vegetation should be the minimum but large enough so that amount water removed through evapotranspiration should equal the total annual recharge.
- Salt tolerance: Salt tolerance will be an important criterion for (potentially) saline discharge environments, water use considerations will prevail in recharge control situations where salinity is of no concern and in channel seepage scenarios with low-salinity water supply. Water use capacity of trees decreases with increase in water salinity. Therefore, biodrainage crops need to be salt tolerant.
- Drawdown of water table: Crops, including trees, act as bio pumps; they depress the water table directly underneath plantation areas and consequently lower the water table in the surrounding area. Draw down effect depends on water use capacity of trees, rate of recharge in surrounding area, soil hydraulic conductivity, depth of deeper barrier layers, root system of trees and salt-tolerance of tree species.
- Salt balance: Salt balance determines the sustainability of plant water use and lowering of water table. If the salts moving into the root zone are not either (i) taken up by the vegetation and harvested or (ii) removed from the root zone by leaching, the vegetation will succumb to salinity. Large volumes of irrigation water even of low salinity significantly increase salt imports. Salinity buildup beyond a threshold level will certainly hamper plant growth. To achieve the salt level below the critical level, drainage of these salts below the crop root zone is considered a necessity for optimum plant growth. The Israeli experience has shown that the bio-drainage technique can

effectively lower a shallow water table and reverse salinity trends, provided that the overall water balance is negative, i.e. that the water inputs match the water use by the tree plantation and local drainage characteristics (Gafni and Zohar, 2007). In absence of conventional drainage, the irrigated crops and biodrainage vegetation should be salt accumulating so that salts introduced by irrigation can be removed through crop harvest. But the ability of the biodrainage system to maintain a salt-balance is not clear. The salt uptake by plants in general is negligible compared to the total salt applied in irrigation supplies as trees do not bio-harvest as the roots exclude salts during water uptake making a saltwater lens below the root zone (Chhabra and Thakur, 1998; Heuperman, 1999). Chhabra and Thakur (1998) reported that 3 year old Eucalypts (*Eucalyptus tereticornis*) and 4 year old bamboo (*Bambusa arundinacea*) having low groundwater salinity 0.4 dS/m and water table depth 1.5 m had very high biodrainage value (plant water use) up to 5.5 m and 4.2 m per year, respectively. Biodrainage values were lower at the higher groundwater salinities. In high-salinity environments plant salt uptake might be negligible in relation to the salts present in the system, under low-salinity scenarios salt balance by plant uptake and removal might be achievable (Heupermanet et al., 2002). On dry weight basis, mineral content in leafy vegetables is reported 14 % followed by other vegetables (8%), roots and tubers (6.5%) pulses and legumes (3.5%) and cereal grains (2%) (ICMR, 1989). Maximum soil water salinity which can be controlled by bio-drainage is around 3 dS m^{-1} in medium run (Akram et al., 2008). In cases where bio drainage results in salt accumulation, engineering assistance is needed to make the system sustainable.

- Economic aspects: Biodrainage plantations should be of high economic value so that costs associated with planting and maintenance can be covered from the sale of the tree produce. In direct benefits of planting trees on farm lands in terms of organic carbon build-up, carbon sequestration in biomass and other eco-system services should also be considered.

6. Suitable Plant Species for Biodrainage

The vegetations with profuse transpiration ability appear to be a promising tool for improvement of drainage situation through removal of excess water. Consumptive water use of plants varies with the age, geometry and soil water and salinity and climatic conditions. The rate of fall of the water table doubled with the development of the trees (Rodríguez-suárez et al., 2011). It has been demonstrated that under ideal conditions, consumptive use of trees varies between 6500 to 28000 m^3 ha^{-1} $year^{-1}$ and a tree canopy may lower water tables by 1–2 m over a time period of 3–5 years (Gafni and Zohar, 2001; Heuperman et al., 2002; Kapoor, 2001, NIH, 1999). For biodrainage, amongst different trees, Eucalyptus has been used the most for this purpose because of its luxurious water consumption (Dong et al., 1992). The roots of Eucalyptus penetrate in the soil at 2.5 meters per year and utilize ground water as well as water from upper vadose zone (Calder et al., 1997). It goes straight thus low shading effect, reduces groundwater recharge with minimal competition with adjacent crops for water and grows well under a wide range of climatic conditions (White, 2002). In waterlogged areas, it can be successfully grown by ridge planting. The world's Eucalyptus plantation area has increased to 19 million ha because of its fast growth rate, favourable wood properties and carbon sequestration and thus seems to be a good option for biodrainage (Iglesias Trabado et al., 2009). Eucalyptus species use more water than native species of trees (Zahid et al., 2010). Early studies in Australia (Greenwood et al., 1985) suggested that the rates of transpiration and groundwater uptake by Eucalyptus underlain by relatively shallow (5-8 m below surface) water tables were 3-6 higher than from pasture. In Israel, annual transpiration of three-year-old trees *E. Camaldulensis* was found to be 1,360 mm (Zohar et al., 2008). In Indian desert, plantation of *Eucalyptus camaldulensis*, *E. fastigata*, *E. rudis* and *Corymbia tessellaris* on raised bunds, improved vegetation cover with simultaneous decrease in water table. Performance of *E. rudis* was found to be the best with respect to growth, biomass, transpiration rate and overall bio-drainage potential (Bala et al., 2014). Average over a period of six years the evapotranspiration rate of Eucalyptus was reported to be 3446 mm per year. In Australia, 8 years old Eucalyptus plantation lowered the water table 2 meters or more and piezometric head by 1.5 m (NIH, 1999). In Western Australia, annual tree water use values for *Eucalyptus Camaldulensis* ranged from 0.6 A pan for irrigated Eucalyptus with full canopy cover (Marshall and Chester, 1991) to 1.9 Apan irrigated with seepage affluent (Morris and Wefner, 1987). Water use of 3-5 years old *Acacia nilotica* was found to be 1248 and 2225 mm per annum on severe and mild saline soils, respectively (NIH, 1999).

Studies conducted on abandoned waterlogged degraded land in Haryana, India to lower down water table found trees like *Eucalyptus* hybrid, *Eucalyptus tereticornis* C-10, *Eucalyptus tereticornis* C-130 and *Prosopis juliflora* fast biodrainers, *Eucalyptus tereticornis* C-3, *Callistemon lanceolatus* and *Melia azedarach* in the category of medium biodrainers whereas *Terminalia arjuna* and *Pongamia pinnata* slow biodrainers. An overall 20 cm decline in water table was recorded during the 5th year growth compared to control (without plantation). Leaf area was found to be a cardinal component of biodrainage potential. (Toky et al., 2011). To make use of unproductive land and lower the elevated groundwater table (GWT) suitability of 9 multipurpose trees (*Prunus armeniaca* L.), black poplar (*Populus nigra*), black willow (*Salix nigra*), Eastern catalpa (*Catalpa bignonioides*), Euphrates poplar (*Populus euphratica* Oliv.), Russian olive (*Elaeagnus angustifolia* L.), salt cedar (*Tamarix androssowii*), Siberian elm (*Ulmus pumila* L.), swamp ash (*Fraxinus pennsylvanica*), and white mulberry (*Morus alba*) for biodrainage were studied on sandy and loamy slightly saline soils on degraded agricultural landscapes in Khorezm, Uzbekistan, Aral Sea Basin. *E. angustifolia* ranked the highest, combining high water use, fast growth and production of nutritious feed. *Populus* spp. and *Ulmus pumila* L. ranked lower but still represented potential candidates for biodrainage purposes whereas fruit species such as *P. Armeniaca* and *M. alba*, though desirable from the farmer’s financial viewpoint, showed low biodrainage potential. The annual stand transpiration amounted to 1830, 1470, and 730 mm for *E. angustifolia*, *U. pumila* and *P. euphratica,* respectively. Transpiration rates was highly correlated with length of fine roots whereas weakly correlated with leaf area and no correlations were found between salt content in plants and water uptake under conditions of slight-to moderate root zone soil salinity (Khamzina et al., 2006). In north-western China, *Lycium barbarum* and *Puccinellia Chinamponsis* proved to be very effective in lowering shallow ground-water tables and facilitating some leaching of salts from the surface layers (Zhao et al., 2004). Other suitable species for block plantations are *Populus deltoides*, *Casuarina glauca*, *Terminalia arjuna, Pongamia pinnata and Syzygium cuminii* etc. Apart from the planted species, *Prosopis juliflora*, *Tamarix dioca* and *Saccharum munja* also have come up in the area with recession of ground water table as natural succession and contributed significantly for further lowering of ground water table and increasing productivity. The well managed multipurpose tree species on farm enhance the overall productivity, improvement in soil fertility, soil conservation and nutrient cycling, micro-climate amelioration, carbon sequestration, bio-drainage, bio-energy and bio-fuel production etc. There is consensus that biodrainage, when properly implemented, can lower the water table and solve problems associated with waterlogged areas and canal seepage (Ahmad et al., 2007).

Though problem of salinity can be managed by removal of excess groundwater through the transpiration by vegetation thus lowering down the water table below the root zone but the performance or suitability of biodrainage in saline conditions is still a debateable issue. According to Kapoor and Denecke (2001) biodrainage could be used in various regions ranging from humid to semi arid areas, except when the ground water EC is greater than 12 dS m^{-1}. However, Akram and Liaghat (2010) are of the view that biodrainage does have a high sensitivity to salinity in regions with arid and semi arid climates. Biodrainage cannot be a good alternative to conventional drainage systems when the irrigation water is too saline. Due to increasing salinity over the time, evapotranspiration efficiency of the tree strips reduces to such an extent that actually will lose its applicability. Horticultural and landscape plants indicate 100% loss of relative growth or yield at 8, 16, 24 and 32 dS m^{-1} for sensitive, moderately sensitive, moderately tolerant and tolerant crops, respectively (Blaylock. 1994). Levels of 4 to 5 dS m^{-1} affect many crops and above 8 dS m^{-1} affect all but the very tolerant crops (Cardon et al., 2011). In the case of Eucalypt species, it reduces to about one-half of potential when the water salinity increases to about 8 dS m^{-1} (Oster et al. 1999). Yet there are many plant species which are tolerant to salinity and grows well.

Eucalyptus occidentalis performed better than *E. camaldulensis* under the more saline situation emphasizing selection of salt tolerant species. The annual transpiration of Eucalyptus in saline environment highlighted the ecological benefit of eucalyptus plantations in lowering the water table, even in a saline habitat, although their economic viability under such conditions remains limited (Zohar et al., 2008). Singh et al. (2013) were of the view that bio-control measures involving selection of more salt-tolerant crops, residue management, and biodrainage manages soil and water salinity for sustainable agriculture. The Central Soil Salinity Research Institute (CSSRI) at Karnal, India, presents data on the tolerance of tree species to soil salinity as shown in Table 4 (Tomar and Gupta, 1999).

Table 4. Suitability of tree spp. for saline soils

Tolerant (ECe 25-35 dS/m)*	*Tamari troupii, T. articulata, Prosopis juliflora, Pithecellobium dulce, Parkinsonia aculeata, Acacia farnesiana*
Moderately tolerant (ECe 15-25 dS/m)	*Callistemon lanceolatus, Acacia nilotica, A. pennatula, A. tortilis, Casuarina glauca, C. equisetifolia), Eucalyptus camaldulensis, Leucaena leucocephala*
Moderately sensitive (ECe 10-15 dS/m)	*Casuarina cunninghamiana, Eucalyptus tereticornis, Acacia auriculiformis, Guazuma ulmifolia, Leucanea shannonii, Samanea saman, Albizzia caribea, Senna atomeria, Terminalia arjuna, Pongamia pinnata*
Sensitive (ECe 7-10 dS/m)	*Syzygium cumini, S. fruticosum, Tamarindus indica, Salix app., Acacia deanei, Albizia quachepela, Alelia herbertsmithi, Ceaselpimia eriostachya, C. velutina, Halmatoxylon brasiletto*

* ECe is the average rootzone salinity as measured in a saturation extract
Source: Tomar and Gupta, 1999

7. Case Studies

Number of experimental case studies were taken up from different agencies from India, USA, Australia and other countries. Some of the case studies are given in **Annex.**

8. Advantages

The merits of biodrainage technique over the conventional engineering-based drainage systems are as given below:

- Farmers although realize benefits of drainage but are too poor to pay cost of drainage, whereas raising biodrainage plantations is relatively less costly and affordable.
- Biodrainage requires no maintenance after initial establishment
- No operational cost, as the plants use their bio-energy in draining out the excess ground water into atmosphere.
- Ecologically safe as drainage effluent is not produced.
- Increase in worth with age instead of depreciation
- Preventive as well as curative system for waterlogging and salinity
- Provides recreational areas and green open spaces, supporting beekeeping (Hadas 2001)

- Sequesters carbon and earn carbon credits
- Moderates the temperature of the surrounding by transpiration thereby proofing for heat and cold waves
- Mitigates green house gases by absorbing CO_2 and releasing O_2
- Acts as wind break and protects crops in agroforestry system
- Provides higher income to the farmers due to the production of food, fodder, timber, fuel wood and other valuable products. Thinning, based on harvesting about 50% of the slower growing trees, could provide returns even in about five years. The felled trees might be used as a source of biomass for firewood, small poles for agriculture, and/or pulp production, if markets are available. Better performing trees, could be used to produce wood for household and garden furniture (Zohar et al., 2008).
- Biodrainage stabilizes soil on raised bed as highway avenue plantation
- Subsurface drainage in irrigated areas is a collective activity, thus needs appropriate institutional arrangements for farmers' participation (Ritzema et al., 2008). But in case of biodrainage, there is assured people's participation as the biodrainage plantations on farmer's field belong to the individual farmers.
- The improvement in soil salinity and waterlogging provides additional land for cultivation
- Increase in cropping intensity and soil organic carbon build-up
- More choice among arable crops including pulses and oilseed which otherwise are sensitive to waterlogging and salinity
- Timely sowing of crops thus facilitating better yield and profits
- Higher crop yields and nutrient use efficiency
- Increased employment generation and poverty reduction

9. Constraints

Apart from many advantages, the following limitations of biodrainage may be kept in mind:

- Requires land, may be 10 to 15 % of the total holding of the farmer.
- Requires irrigation for the survival of the trees
- There is a danger of damage in early stages of tree growth
- Tree plantations may not be effective in lowering down the water table in the early growth stages.
- Competition of foliage and roots between trees and crops for light, moisture, nutrient, etc and its effects on co-existing vegetation.
- There is increased activity of the wild animals like blue bull affecting general cultivation
- With age, there would be gradual decrease in capacities of trees for consuming and transpiring water thereby reducing extent of bio-drainage.
- In discharge sites, with evapotranspiration there can be salt accumulation in soil profile which will affect tree growth.
- Where farm holdings are small, obviously landholders are unable to set part of their farm aside for bio drainage activities. Therefore, any application of this technique will have to focus on public land.

10. Future Research and Policy Issues

To further develop the technology of biodrainage, the following issues will need to be considered:

10.1 Research Issues

- **Improving consumptive use of water by trees:** There is wide variation in tree water use values because of changes in climatic conditions, type and age of tree species, size of plantation, density of tree plantations (spacing), soil moisture regime, etc. This makes it difficult to select accurate design criteria for biodrainage tree plantings. What should be the optimum density of tree plantings for biodrainage for maximum evapotranspiration per unit area?
- **Salt balance and salt tolerance:** Further research is required on the mineral absorption by trees and salt-tolerance for estimating salt-balance. The growth of trees and salt-tolerant crops with increasing salt build up in soil profile and consequential impacts on transpiration capacity and excess water removal require further studies in detail.
- **Tree species research:** Biomass production and water use of desert trees like *Prosopis* which are high biomass producing and salt tolerant need to be investigated under conditions of abundant water supply.
- High potential biodrainage tree species and their clones/varieties may be identified for specific agro-ecological regions
- Role of highly transpiring Eucalyptus and other trees (bio- drainage) for control of waterlogging, particularly as a preventive seepage control measure in the vicinity of canals and as well as in appropriate agro- forestry models
- Impact of integrated conventional drainage approaches and biodrainage on controlling waterlogging and soil salinity for sustainability of agriculture and environment
- Process based models to predict salinity within the basin under the present and afforested conditions.
- The suitability of biodrainage plantation in shallow saline water table is still in debate.

10.2 Policy Issues

- Pilot level studies in waterlogged hotspots for better dissemination of biodrainage technology
- Superior planting stock of trees (clones of Eucalyptus, Casuarina, poplar, bamboos, etc.) which are both fast growing and high transpiring in waterlogged saline soils made available to the farmers
- Provide appropriate credit to the adjoining farmers for raising strip plantations along the canals, high ways and railway for interception of seepage and controlling rising water table.
- Minimum support price policy especially for wood and pulp producing biodrainage plantation to avoid distress sale
- Setting of plywood, paper and pulp industries in rural areas to encourage farmers to go for biodrainage
- Incentives for agencies responsible for undertaking biodrainage programmes
- Awareness and sensitization programs on biodrainage for stakeholders may be organized regularly.

11. Conclusion

To solve the twin problem of waterlogging and secondary salinization caused due to agricultural development and use of irrigation increasingly demands the biodrainage plantation of trees and salt-tolerant crops as an integrated part of the landscape and farming viewing the cost and environmental issues involved in using the conventional drainage technologies. Plantation of suitable salt tolerant deep rooted fast-growing trees with high transpiration rates provides benefits in terms of reclamation of waterlogged area, controlling of water table, improving crop productivity, providing shelter belts, provide additional wood and forest products, and biodiversity. The problems associated with a rise in salinity in the root zone can be effectively delayed using biodrainage systems in semi-arid and arid areas. Biodrainage can be effectively used for water table management both in dry lands and irrigated areas. For better performance biodrainage plantation may also be raised on potentially waterlogged areas to prevent their conversion into waterlogged areas. In areas where the groundwater is sweet and is being subjected to over-exploitation for irrigation and other purposes, resulting in a steep fall in the water table plantation of high biodrainage potential trees might decline water-table further. For the proper planning of bio drainage activities assessment of water and salt balance in the landscape is a major requirement. Apart from advantages, biodrainage has its own limitations also as it requires large area of land, may not be very effective removing salts and performance of plantation is affected by increasing build up of salinity in soil profile with time. Where bio drainage results in salt accumulation, engineering assistance is needed to make the system sustainable.

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Annex

*Case Studies o*n The Role of Bio-Drainage for Managing Waterlogging and Salinity

1.1 Biodrainage to control channel seepage in Indira Gandhi Nahar Project, Rajasthan, India

Large areas along the main canal in the Indira Gandhi Nahar Project (IGNP) became waterlogged mainly due to seepage from the canal and presence of impervious gypsum layer at shallow depth. Before IGNP, the depth of water table in the command area of Phase I generally ranged between 40 and 50 m below the surface water table and the quality of groundwater was highly saline and unfit for irrigation. With the introduction of irrigation, the groundwater table started to rise at the rate of 0.92 m $year^{-1}$. In Phase II of the project, the groundwater table before the advent of irrigation generally ranged between 20 to 100 m below surface. With irrigation, it has been rising, though not at the same rate as Phase I. To protect the canal form sand drift and meet the timber, fuel and fodder need of the locals, plantations were raised in the area. The afforestation schemes included canal side plantation, block plantation, sand dune stabilization, pasture development, roadside plantation and environmental plantation. The main trees planted in irrigated areas were *Eucalyptus camaldulensis*, *Dalbergia sissoo* and *Acacia nilotica*, whereas *Prosopis cineraria*, *Tecomella undulata* and *Ziziphus* in unirrigated areas. *Lasiurus sindicus* grass was planted for pastures and in between mulch lines for stabilization of sand dunes. Along the canal, the width of plantation was 100m on the right side and 200 m on the left. Amongst different trees, growth of *Eucalyptus camaldulensis* was the fastest whereas *Prosopis cineraria* the slowest. The annual rate of transpiration was found to be 2971mm, about 1.2 class A pan evaporation (Heuperman et al., 2002; Kapoor and Denecke, 2001). Plantations made along the canal and around the submersed areas removed excess water through biodrainage and the groundwater table fell by about 15 m after six years. As a result of that inundation disappeared from most of the affected area. Considering the annual rate of transpiration of 3000 mm, for maintaining water balance roughly 5% of the area needs tree plantation.

Analysis of factors responsible for waterlogging and salinity in IGNP found were large percolation losses from the irrigated fields, seepage from channels, over use of water for irrigation, relatively low levels of groundwater development, subsurface barriers and absence of natural drainage. An optimal policy to control the problems of waterlogging and salinization require lower water allowance, efficient irrigation methods, conjunctive utilization of surface water and groundwater, planting trees and artificial drainage (Sharma, 2001).

1.2 Eucalyptus based agroforestry system for waterlogged soils at Puthi, Haryana, India

Two plantations 350 m apart comprising of 18 years old *Eucalyptus tereticornis* (Mysure gum) raised at a spacing of 3mx3m along the road and railway line on alluvial sandy loam soil at Dhob-Bhali, Rohtak (Haryana), lowered groundwater table by 0.91 m but no increase in salinity underneath the plantations than the ground water table underneath the adjacent fields without plantation Ram et al. (2007). The spatial extent of lowering of groundwater table in the adjacent fields was up to a distance of more than 730 m from the edge of a plantation.

But in developing countries like India, farmers have small holdings and not interested to put the land under sole forestry plantations which yield after a gap of five to six years. Under such situations, planting trees on farm boundaries in form of agro forestry can be a viable and remunerative option, which will provide regular income also. Parallel strip plantations of

Eucalyptus tereticornis (Mysure gum) spaced at 66 m and each strip-plantation contained 2 rows of trees at a spacing of 1 m x 1 m resulting in a density of 300 plants ha^{-1} lowered the ground water table underneath the strip-plantations by 85 cm compared to adjacent unvegetated fields in 3 years (Ram et al., 2011). In this field study, four parallel strip-plantations of clonal *Eucalyptus tereticornis* were raised in December 2002 on four ridges constructed in north-south direction in 4.8 ha canal irrigated waterlogged fields of farmers at village Puthi, Hisar, Haryana. The shapes of draw down curves of ground water table in both transects were similar to the combined cone of depression of 4 pumping wells working simultaneously for a long period indicating that 4 strip plantations of clonal *E. tereticornis* were also working as bio-pumps. Water table was brought down mainly be due to the luxurious use of water by Eucalyptus plantation which transpired 268 mm per annum against the mean annual rainfall of 212 mm. Location of the research plot is shown as Figures 3(a), 3(b), 3(c) and 4.

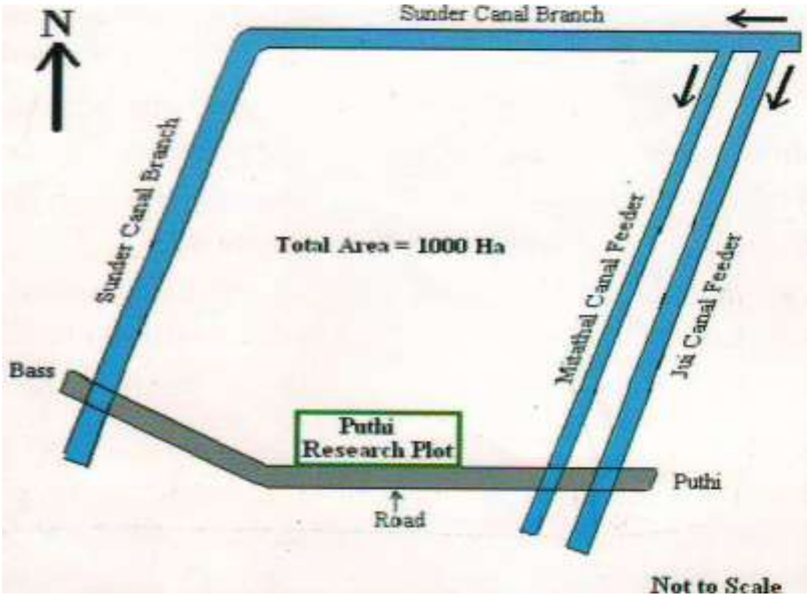

Figure 3(a). Land locked area (Source: Jeet Ram et al., 2008)

Figure 3(b). Mithathal canal and Jui canal feeders (Source: Jeet Ram et al., 2008)

Figure 3(c). Sunder canal branch (Source: Jeet Ram et al., 2008)

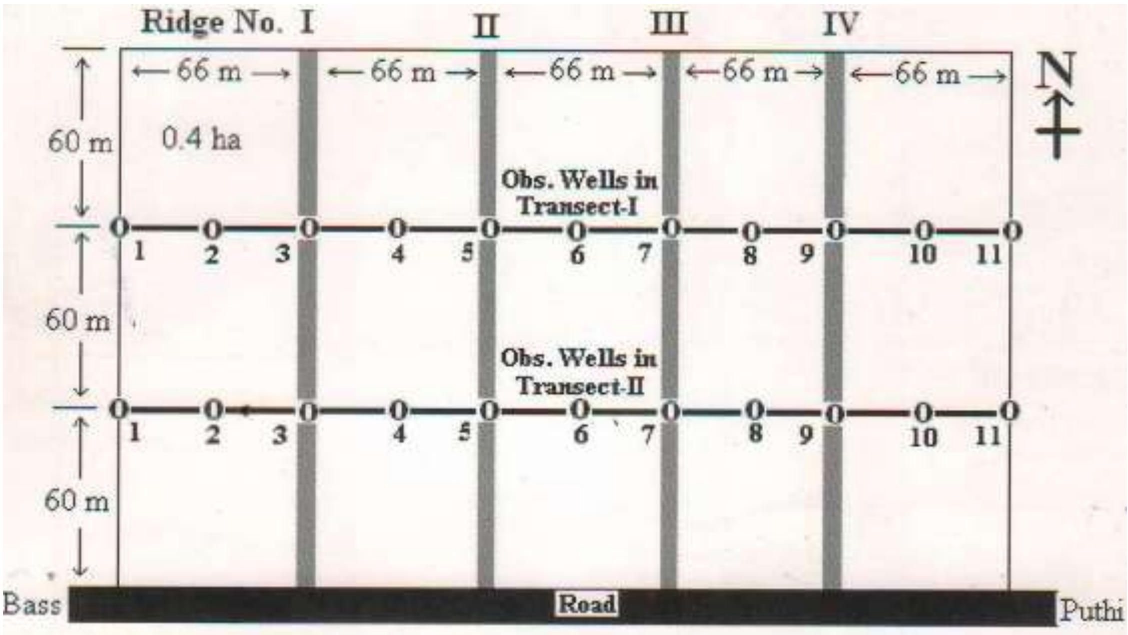

Figure 4. Layout of experiment at Puthi showing position of observation wells and plantation strips (Source: Jeet Ram et al., 2008)

Tree plantations harvested after 5 years and 4 months of growth produced 33 t ha^{-1} of root and shoot biomass and sequestered 15.5 t ha^{-1} carbon. Planting trees requires only initial investment and when established, the system provides economic returns by means of fodder, wood or fibre harvested. In this study, benefit-cost ratio was 3.5:1 for first rotation and would be many folds for next 3 to 4 rotations due to negligible cost of coppiced Eucalyptus. Lowering of water table allowed the farmers to advance sowing of wheat crop by more than two weeks. Due to timely sowing of crop and improvement in soil properties, wheat yield in the inter-space of strip-plantations was 3.4 times the yield in adjacent waterlogged areas without plantation. A view of agroforestry model of biodrainage at Puthi village is shown in Figure 5.

Figure 5. Agroforestry model of biodrainage (Source: Jeet Ram et al., 2008)

The question what should be the optimum spacing of Eucalyptus for strip plantation in agroforestry for achieving maximum benefits in terms of water table draw down, wood production and crop yields was still unanswered. Therefore, above study was continued in the same area by taking strip plantations of clonal *Eucalyptus tereticornis* in paired rows at spacing of 1m x 1m, 1m x 2m and 1 m x 3 m on farm acre boundaries (called killa-lines) spacing resulting in tree population of 300, 150 and 100 trees ha^{-1} (Dagar et al., 2015 personal communication). Considering wood biomass production, lowering of water table, carbon sequestration and crop productivity, agroforestry biodrainage model of six year rotation having strip plantation of Eucalyptus in paired rows on farm acre line in spacing of 1 m x1 m was found better compared to 1m x 2m and 1mx3m in waterlogged areas of north-east India. After effective results shown by the bio-drainage system in checking waterlogging in Haryana, the Punjab Government is replicating the biodrainage system in 3000 hectares of waterlogged area in Muktsar district (The Tribune, 19th April, 2013).

In Indira Gandhi Nahar Project (IGNP) Rajasthan (India) also tree plantations established along the canal lowered ground water table by 14 m in six years (Kapoor, 2001). The main reasons for the difference in drawdown of ground water table at the two sites (IGNP and Puthi research plot) were the design and density of plantations and the sources of recharge in ground water.

1.3 Biodrainage for reclamation of waterlogged deltaic lands of Orissa, India

Biodrainage potential of Casuarinas on land at two sites with groundwater table at 102 and 127 cm in coastal delta, Orissa suffering from waterlogging due to sea water intrusion and Eucalyptus at another two sites on waterlogged soils having groundwater at 150 and 167 cm, respectively caused due to topographical depression were compared by Roy Chowdhury et al (2011). At all the four sites, effects of biodrainage plantation on water table were clear and lowered it by 15 to 25 cm compared to non-vegetated area. As far as efficiency of drainage by plantation or tree water use per se is concerned, greater decline of water table underneath Eucalyptus compared to Casuarina indicated Eucalyptus was found more efficient than Casuarina. Therefore, Eucalyptus plantation was superior in providing drainage relief through intercepting water from deeper soil profile, compared to that under Casuarina plantation in topographically depressed area. This accelerated drainage has helped the farmer to advance *rabi* cultivation by a period of 15-20 days. Due to this, farmers were able to take watermelon in Casuarina and groundnut in Eucalyptus plantations and earned additional benefit. Yield of rice in Casuarina got improved but in Eucalyptus the crop yields were reduced after two years due to the shading effect and competition with intercrop for nutrients and other resources. Overall, the principle of bio-drainage to lower the rising water table with *Eucalyptus* and *Casuarina* vegetation appears promising. The successful intervention with pisciculture, integration of intercrops and crops like watermelon in reclaimed area is also feasible to enhance productivity of areas which otherwise remain sub-productive due to waterlogging. Therefore, high rate transpiring trees like Eucalyptus plantation may be grown for topographically depressed inlands and canal seepage interceptions and may be grown parallel to the field drainage options as an alternative. Similarly salt tolerant tree species like Casuarina may be a good option in coastal waterlogged areas. In Australia also, Casuarina performed better on shallow saline soils (Cramer *et al.* (1999) for lowering ground water table.

1.4 Control of shallow water table by block plantation of Eucalyptus at Kyabram, Australia

Large scale clearing of deep rooted forest trees with shallow-rooted annual crops and pastures followed by introduction of irrigation resulted in rise in water table from 30 m (before clearing) to 2 m or less and development of soil salinity at Kyabram, Australia (Heperman, 1999; Heuperman et al., 2002; Ferdowsian et al., 1996; George et al., 1999). Low returns from the agricultural production systems and the high costs of drainage engineering compelled to go again for planting deep-rooted permanent pastures, crops and trees for achieving a plant water use scenario that more closely approximates that of the pre-clearance situation. Trees lower water table through higher rates of transpiration than shallower rooted and often more salt sensitive crops and also provide timber wood, fuel, fodder to the farmers. During the study period, average rainfall in the region was 480 mm $year^{-1}$ with an annual average of evaporation 1403 mm. The soils of the sites were loam *Natrixeralf,* a red brown duplex soil. The site was planted with Eucalyptus, irrigated with freshwater for initial six years and attained increments in height of up to 2.5 m $year^{-1}$ measured during that period.

The average water table level at the plantation site in February 1977 (two years after tree establishment) was 1.94 m below the surface. Seven years after tree establishment, the trees significantly lowered down the water table underneath the plantation and its impact was observed up to 50 m into the irrigated pasture. As the trees exclude salts during water uptake, salinities in the upper part of the saturated zone (near the water table) underneath the plantation increased. At most of the points in plantation sites, water table salinities increased over the period (1982-1993) reflecting this salt concentration process. In 1993, water table salinities under the trees were clearly higher than outside the plantation. The salt accumulation was recorded between 2.5 and 5.5 m in the profile from the surface.

At another site in the same region decline of the water table was linearly correlated with tree spacing. The decline decreased with increasing tree spacing. The effects were conspicuous after four years of planting. For every 10 percent increase in planted area, the water table was lowered by about 0.4 m.

1.5 Integrated management of saline drainage effluent, USA

Disposal of drainage effluent in the San Joaquin Valley, caused selenium toxicity and bio-accumulated salts at high levels in plants and animals enough to cause mortality and to impair reproduction of fish and aquatic birds. Aquatic plants, invertebrates, fish, frogs, snakes, birds and mammals at Kesterson Reservoir contained elevated selenium levels, often averaging a 100-fold increase over samples collected for similar species at reference sites (Ohlendorf, 1989; Ohlendorf and Santolo, 1994). Therefore, combination of bio- and conventional drainage approach to drain water management was designed and demonstrated on a farm in the Central Valley in California (Cervinka *et al.,*1999).

Farm as a whole covers 620 acres and has 4 salinity zones. Out of these 3 zones each of 157 acres were planted with salt sensitive vegetables and provided with subsurface tile drainage. Similarly, independent drainage systems operated for salt tolerant crops/trees (130 acres) and salt-tolerant grasses (13 acres), whereas shared drainage system for the halophytes (5 acres) and the solar evaporator (2 acres). Vegetables were grown in non saline zone and irrigated with canal or well water, whereas crops like cotton, alfalfa in low saline zone and received water from tile drainage, tail water (from vegetables), and of canal/well water vegetables. Salt tolerant trees and grasses were grown in moderate saline zone covering two per cent of the project area and irrigated with drainage water from salt tolerant crops. Similarly, saline water from salt tolerant trees and grasses was used in halophytes. This sequential water reuse process productively uses over 90 percent of the drainage water. The remaining drainage water goes into a solar evaporator where water was evaporated and salt crystallized. Sequential reuse of drainage water increased the overall efficiency of water use. The system also prevented on-farm drainage water from contributing to severe regional problems of poor groundwater quality and high water tables. Overall there was a net increase in crop yields and vegetable production grown in non saline areas. Basically an integrated bio- and conventional drainage system managed irrigation water, drainage water, salt and selenium as resources within the boundaries of the farm and not discharged into rivers or lakes. It seems viable eco-friendly sustainable system for managing water logging and salinity at the farm level. This innovation has great potential for up-scaling in other parts of the world by incorporating location specific adjustments.

1.6 Biodrainage potential of Eucalyptus for wastewater disposal

Tree plantations are often expected to use water at higher rates than the shorter vegetation. This is because of greater aerodynamic roughness of tree plantations, clothesline effect in tree rows and deeper rooting system for accessing water down to several metres of soil. Therefore, biodrainage potential of trees having very high transpiration rates can also be exploited for recycling and reuse of wastewater and converting nutrient energy into wood biomass and improving environment. Very high rates of wastewater disposal (0.3–1.0 million litres day^{-1} ha-1) in *Eucalyptus tereticornis, Leucaena leucocephala* and *Populus deltoids* plantation were reported by Chhabra (1995). Morris and Wehner (1987) reported annual crop factors of 1.4–1.9 times the open pan evaporation (PAN-E) and the maximum daily water-use rates of 20 mm in summer (January) by 3-year-old Eucalyptus plantations irrigated with effluent in arid western Victoria, Australia. With the advancement in measurements of water use, transpiration rate by Eucalyptus plantations estimated by thermo-electric heat pulse method were found to be lower than the reported earlier. In Pakistan, water use to the tune of 0.86*PAN-E was reported from the saline sites (Khanzada et al., 1998; Mahmood et al., 2001). Some of the recent studies (Kallarackal and Somen, 2008; Forrester et al., 2010; Hubbard et al., 2010) show similar results but the overall water use by trees seems to vary a lot with the specific site conditions defining soil type, evaporative demands, stocking density and even the salinity determines the actual water use. In a ten year study conducted at CSSRI, Karnal by Minhas et al. (2015) Eucalyptus plantation irrigated with sewage performed better than the groundwater. Consumptive water coincided with tree growth rates and increased until sixth year of planting and stabilised thereafter. The annual sap flow values ranged between 418–473, 1373–1417 and 1567–1628 mm during 7–10 year of planting under low (163 stems ha^{-1}), recommended (517 stems ha^{-1}) and high (1993 stems ha^{-1}) stocking density respectively. In the nutshell, Eucalyptus plantations can act as potential sites for year round and about 1.5 fold recycling of sewage than the annual crops. Layout set up of the experiment at Karnal farm is depicted in Figure 6.

Figure 6. Measurement of transpiration rate with sap-flow meter
(Source: Jeet Ram et al., 2008)

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